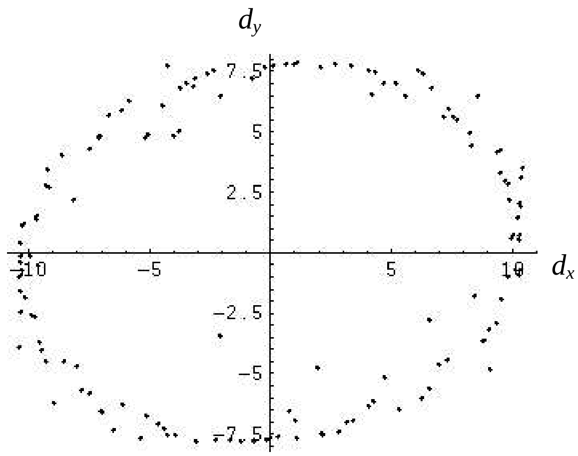

Figure 1. Beams separation in units of the pbar r.m.s. beam sizes.

Energy,	GeV	150
N_p /bunch,	10^{11}	2.7
ε_p (95% normal.),	$(\pi)\cdot$mm$\cdot$mrad	20
ε_{pbar} (95% normal.),	$(\pi)\cdot$mm$\cdot$mrad	15
σ_E ,	10^{-4}	4.0
ν_s ,	10^{-3}	1.8

Table 1. Parameters used in calculations.

1 Motivation

Long-range interactions can present much greater danger at the injection than in collision due to:

- Smaller (on average) vertical separation between the beams (see Fig.1);
- Very small separation (just 4σ!) at one of the interaction points (that at 5236m from B0);
- Higher chromaticity, energy spread and synchrotron tune increasing the number and strength of the synchro-betatron resonances (SBRs).

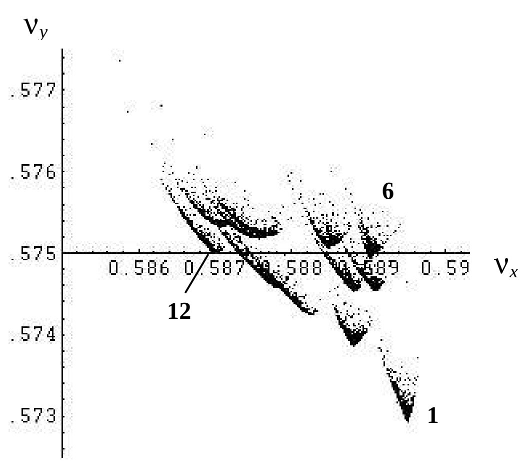

Figure 2. Distribution of pbars in the plane of the betatron tunes, bunches ##1, 6 and 12 are pointed out.

Here we analyze the effects of the long-range interactions – shifts in tunes and chromaticities, excitation of SBRs – ignoring the effects of the lattice nonlinearities which can also be important.

2 Tuneshift

Fig.2 shows the total footprint of a train of 12 pbar bunches in the plane of the betatron tunes obtained by randomly distributing 3000 particles/bunch in the betatron amplitudes with a Gaussian distribution function. The bare lattice tunes assumed to be 20.585, 20.575.

All particles seem to be sufficiently far away from low (5^{th} and 7^{th}) -order resonances, however with large chromaticity and energy spread synchrotron satellites of very high order can be excited that reach the tunespread.

3 Bessel satellites

The main mechanism of the SBRs excitation is the betatron tune modulation due to large chromaticity. The relative strength of the m_s-th satellite of the $m_x\nu_x + m_y\nu_y$ = integer resonance is

$$b_{m_s} = \mathrm{J}_{m_s}\left[\frac{(m_x\nu'_x + m_y\nu'_y)}{\nu_s}\sigma_E a_s\right], \qquad (1)$$

where the prime denotes differentiation by the momentum deviation δ_p, a_s is the relative synchrotron amplitude.

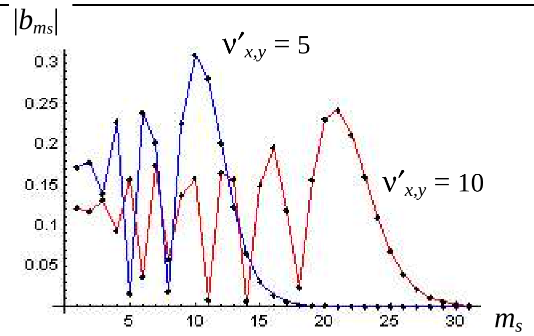

Figure 3. Dependence of the Bessel factor (1) for the 7th order resonances on m_s at the indicated values of chromaticity and other parameters as given in Table 1.

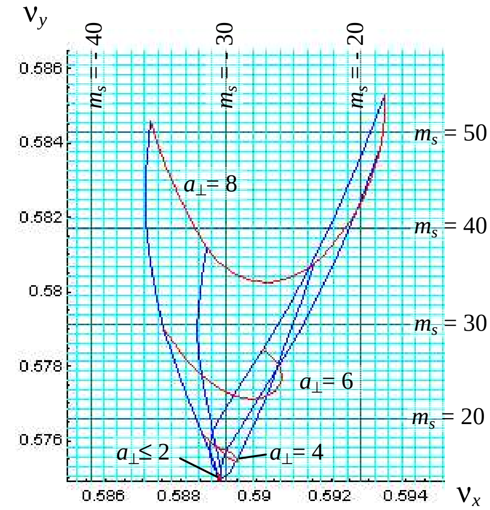

Figure 4. Bunch #6 footprint on the grid of satellite lines of $5\nu_x$ and $7\nu_y$ resonances.

The Bessel factor (1) for the 7th order resonances, $|m_x| + |m_y| = 7$ is plotted in Fig.3 for two values of chromaticity. At the nominal Tevatron values $\nu'_{x,y} = 10$ the sidebands of as high order as 25 can be important[1].

It should be emphasized that due to a relatively small value of the synchrotron tune and high order of the generic betatron resonance (5, 7) the sidebands are very close to each other so that the Chirikov overlap condition is easily met.

Figure 4 shows the footprint of bunch #6 in the tune diagram against the lines of the synchrotron satellites of $5\nu_x$ and $7\nu_y$ resonances. The red lines in the footprint correspond to constant values of

$$a_\perp = \sqrt{a_x^2 + a_y^2} \tag{2}$$

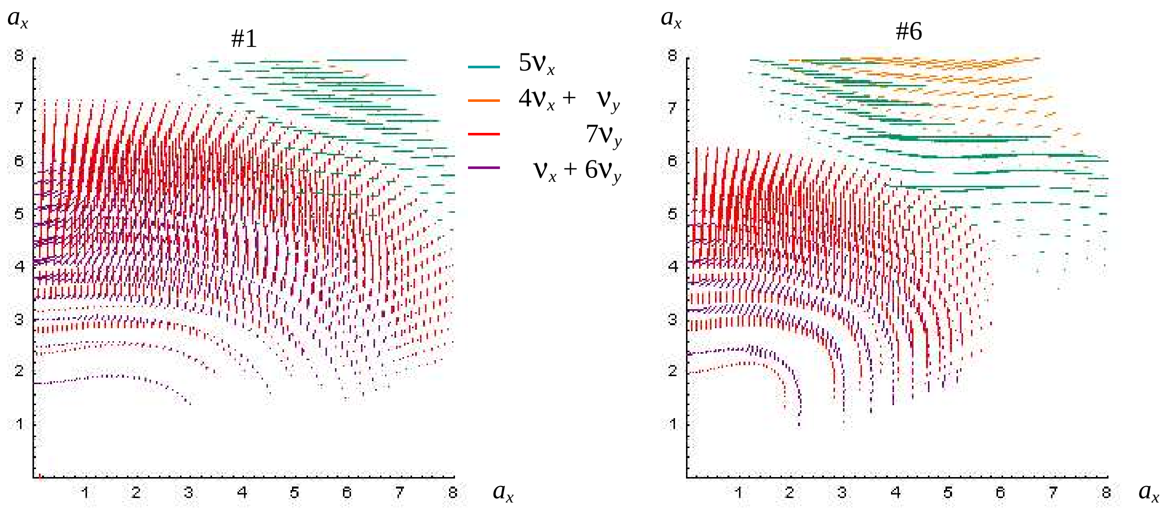

Figure 5. Beatings of the betatron amplitudes in bunches ##1 and 6 due to the sidebands of the indicated resonances at $a_s = 1.414$, nominal proton intensity.

[1] Please note that the number of the important satellites is ~ to the resonance order, therefore in the Schottky spectra of the dipole oscillations (order 1) the satellites up to $m_s = \pm 3$ should be visible at these values of chromaticity.

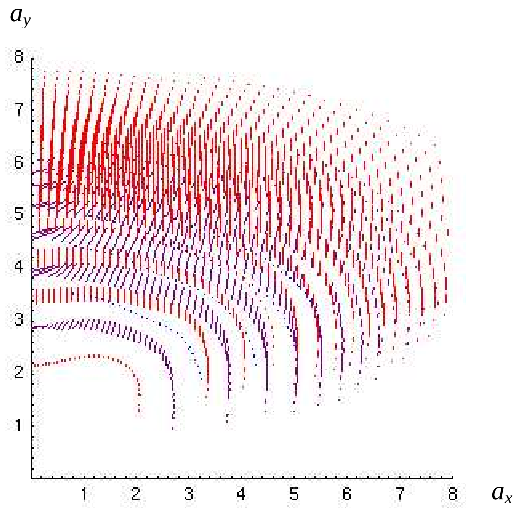

Figure 6. Beatings of the betatron amplitudes in bunch #6 due to the 7th order resonances at half proton intensity.

where $a_{x,y}$ are the betatron amplitudes in units of the pbar r.m.s. beam sizes. The blue lines correspond to constant values of the ratio a_y/a_x. It is worthwhile to note that the beam-beam interaction fails to produce a noticeable tuneshift at amplitudes $a_\perp \leq 2$.

Figure 5 shows the width of synchrotron sidebands of the 5th and 7th order resonances in the betatron amplitudes space for bunches ##1 and 6 at the normalized synchrotron amplitude $a_s = 1.414$ ($\delta_p = 5.7 \cdot 10^{-4}$). Only those resonances whose width exceeds 0.002 are shown.

The 7th order resonances occur to be strong enough to produce large beatings in vertical amplitude (comparable to the distance between the resonances) at $a_\perp \approx 3$ already, and as a consequence can lead to a fast diffusion starting from these amplitudes.

With reduced by half proton intensity the width of these resonances in the betatron amplitudes space is still quite large as illustrated by Fig.6: a decrease in the resonance driving terms is counteracted by a reduction in the detuning with amplitude which plays a stabilizing role.

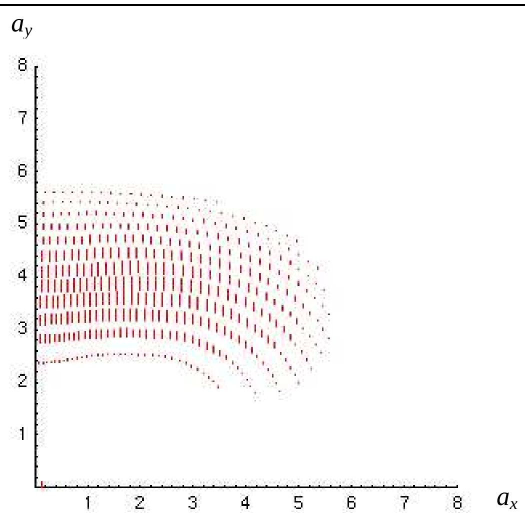

Figure 7. Beatings of the betatron amplitudes in bunch #1 at the nominal proton intensity and $\nu'_{x,y} = 5$.

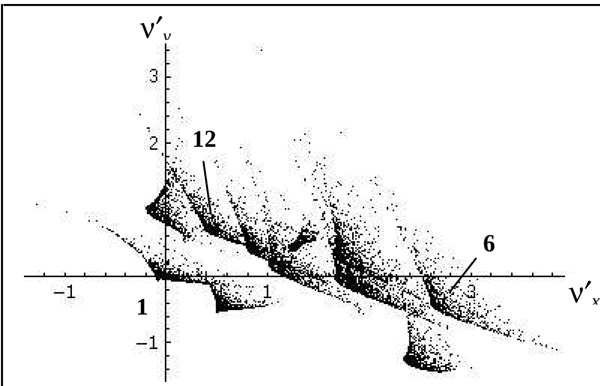

Figure 8. Beam-beam chromaticity at the nominal proton intensity.

4 Effect of chromaticity

Bunch #1 suffers the largest tuneshifts (see Fig.2) and therefore sees the lowest order sidebands which, at chromaticity 10, have smaller width than those seen by bunch #6. E.g. the 11th sideband of the $7\nu_y$ resonance encountered by particles with $a_y \approx 3.2$ is almost completely suppressed (see Fig.3).

With reduced chromaticity the number of strong sidebands diminishes (Fig.3). At $\nu'_{x,y} = 5$ no visible SBR in bunch #6 remains, however, lower order sidebands of the $7\nu_y$ resonance seen by bunch #1 become stronger (Fig.7).

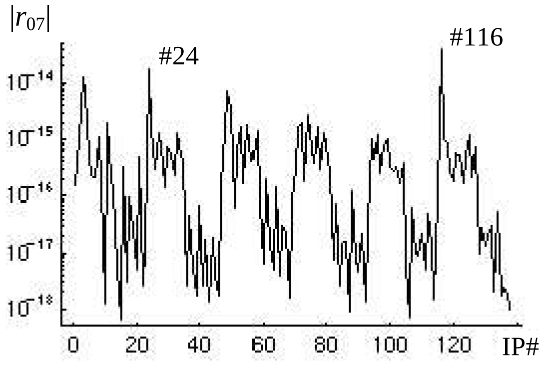

Figure 9. Contribution to $7\nu_y$ resonance at a_y=2.83 from each of 138 interaction points possible with 36×36 bunches (B0 = #1).

Therefore it is not sufficient just to reduce the chromaticity in order to ensure good lifetime of all pbar bunches, in addition to that the vertical bare lattice tune should be increased by an amount of 0.0025 (at chromaticity 5) up to a value about ν_{y0} = 20.5775.

4.1 Beam-beam chromaticity.

Resonance widths shown in Figs.(5-7) were calculated at constant values of chromaticity. However, there exists a contribution from the beam-beam interactions, which introduce chromaticity dependence on the betatron amplitudes as well as the bunch-to-bunch variation. The total distribution is shown in Fig.8. The full spread at the nominal proton intensity exceeds 4 units in both planes, therefore it can not be made smaller than that for all particles.

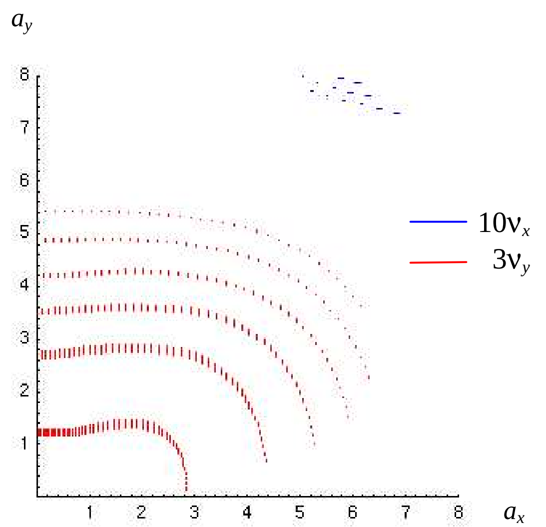

Figure 10. Beatings of the betatron amplitudes in bunch #1 at the bare lattice tunes 20.685, 20.677.

5 Options to consider

The following measures can be helpful but require additional analysis:

- Reducing the pbar transverse emittance and energy spread in order to diminish the number of particles seeing strong resonances.
- Reducing the chromaticity on the pbar helix with the help of octupoles.
- Reducing the value of chromaticity which is necessary for the proton beam stability with Landau damping octupoles (or TELs?).
- Changing the separator settings so as to avoid close encounters: resonance excitation at small amplitudes comes mainly from IP #116 at 5236m from B0 (see Fig.9).
- Moving to another working point: a promising option is a WP around 20.685, 20.675; however the sidebands of the $3\nu_y$ resonance can be quite dangerous. To get an idea their widths were calculated with the helices for the nominal WP. It turned out that to avoid the sidebands overlap the vertical tune should be shifted up (Fig.10).